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VIBRATION EXPERIMENTS

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The design of military vehicles is a rather complicated mixture of many technical activities. In each new development of a tank, truck or jeep, a substantial amount of engineering ideas are required to be blended together to bring forward vehicles possessing features and merit of advanced capability.

While each vehicle development is a separate and distinct program, there are development goals and problems that continually reappear and appear to be common. For example, it is always important to create a good suspension system and it is equally important to provide a dynamically stable vehicle.

The Suspension System is vital for it determines the vehicle ride and vibration behavior and it also establishes the tolerable speed limit of travel over various terrain surfaces, both for the man and the machine.

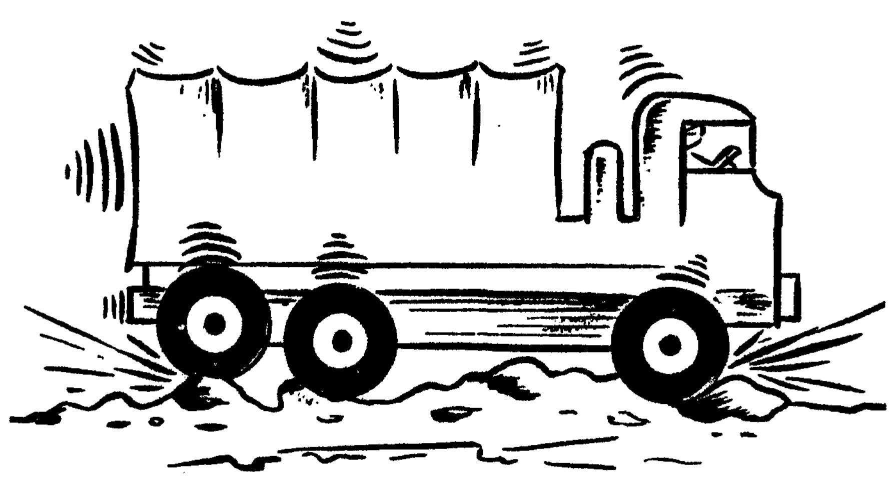


FIG. 1. STEP ONE

Vehicle stability is a design area that also receives considerable attention, particularly in combat vehicle programs where large caliber weapons are expected to be fired from chassis of reduced weight and decreased size. Within military circles reference to vehicle stability differs from the usual automotive connotation. In place of steering behavior or directional control, vehicle stability pertains to pitch and roll movement, resulting from the gun recoil forces.

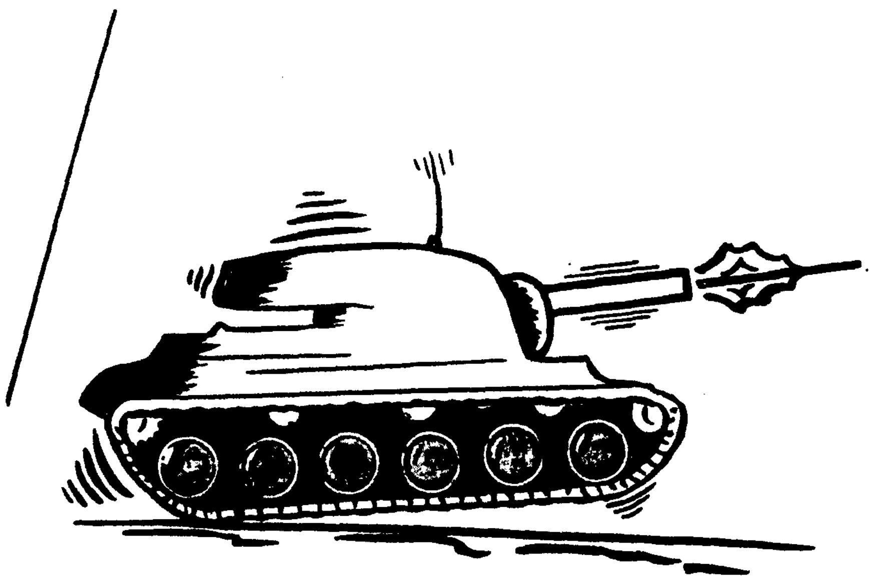


FIG. 2. STEP TWO

These two elements of vehicle design can be considered as perennials. They are always around and unfortunately they are rather "tough nuts" to handle. Individually they present major stumbling blocks to design engineers. Normally, useful study of these problems is beyond the level of developing a new layout or "cranking" through several equations on a desk calculator. As a result, the magnitude of each task has produced design specialists. These people, however, are not medicine men who consistently are able to generate successful answers.

They need help; they need either physical or analytical means to guide and measure their design approaches. Consequently, knowledge of these systems must be consistently bolstered and expanded. This demand requires unique capability:

First, since all wheeled and tracked vehicles are earth bound, knowledge of road profiles or terrain contours upon which they move must be secured.

Next, detailed mathematical models are necessary that describe the vehicle and how it reacts to external disturbances or internal design changes.

Then, an accurate recording procedure is essential to transmit results from high speed computers in such format that their meaning may be assessed graphically, visually or physically.

The benefits of integrating these steps would be a complete capability for realistic design evaluation comparable to controlled tests at a proving ground.

Accordingly, the Army Tank-Automotive Command sought a means to physically simulate the suspension performance and stability dynamics of a design while it was still in the blueprint stage, and to bring together the theory, mathematics and computer machinery to study each of these problems indoors in the laboratory. It was also the feeling that if this program was to be successful, it must produce the ability to predict behavior and allow practicing engineers the opportunity to pretest their designs before commitment to fabricate expensive wood mock-ups, experimental test rigs or engineering prototypes.

Suspension Simulation:

Simulation of vehicle suspension systems is basically the task of predicting the motion response of the vehicle to disturbances from the road. A thorough understanding of the elements that constitute this system and their interrelationship is essential to such study. Beginning with the road is perhaps logically the first step. The basic requirement is to present to the wheels, springs, and shock absorbers, the vertical displacement and frequency identical to those existing in road or terrain surfaces. For this purpose it is possible to construct a computer model of a road profile using either digital or analog computer techniques. The basic data profile information may be secured by conventional rod and transit means or automatic measuring instruments.

In real life the road is a stationary wave form over which the vehicle travels. The relationship between car velocity and the static road generates the suspension dynamics.

In a computer simulation the vehicle's forward movement cannot be faithfully reproduced. To conveniently maintain an order of reality the road is moved instead. The road profile is presented to the suspension components, as a continuous rearward velocity that normally would be road speed.

To accurately duplicate the physical case the road is presented to each wheel separately, properly phased so that the rear wheels "see" the same road irregularities as the front wheels, although at a later time. This phasing is governed by the wheel base and vehicle speed.

One successful procedure of road profile generation utilizes a digital computer and a digital-to-analog converter. The digital machine stores the road profile data in elevation increments. It selects the elevation that each wheel requires at a particular time and generates the time between elevations.

Several preliminary considerations which must be resolved before the construction of such a digital road function include:

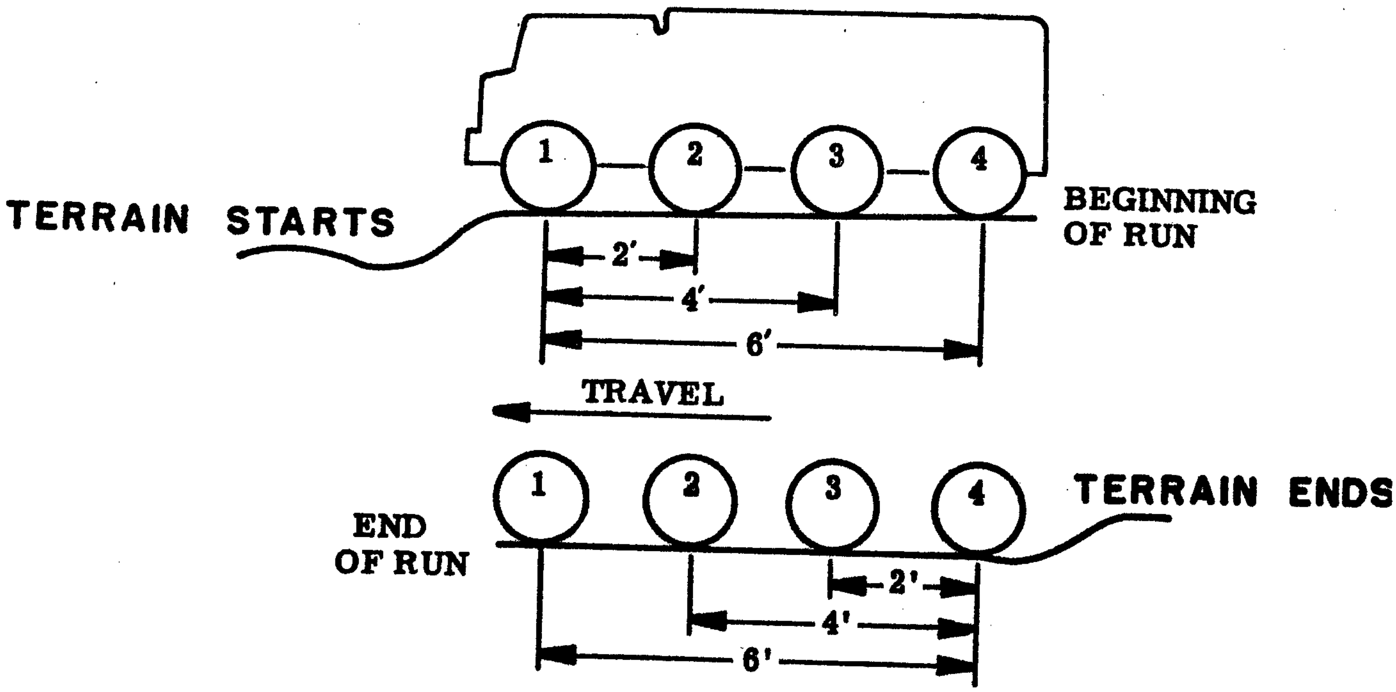
1. The number of vehicle wheels.
2. The spacing between wheels.
3. The starting road level.
4. The number of computer cells per road increment.
5. Overall length of the road profile.

The time at which a particular point on the road will arrive at each wheel is determined by the wheel spacing. This spacing is also considered in deciding how many elevation values will be equivalent to one linear foot of road. The following example will illustrate these points.

A vehicle suspension is set up on the analog computer; this simulation is for one side of the vehicle only, it being assumed that the other side is identical. The vehicle has four wheels on a side, spaced two feet apart. It will be driven over a Belgian Block type road. The road consists of 307 elevations spaced one foot apart. These things being known, it is possible to prepare a scheme for generating the road function which will pass under each wheel in sequence. To rerun the road after once traversing it, a starting road level must be assumed, usually the initial starting elevation, or very near to it. For the conditions just outlined a situation similar to that shown in Figure 3 will exist.

Preliminary assumptions:

1. Vehicle is sitting on road level.
2. Start of road strikes 1st wheel
3. One computer word = 1 linear ft.



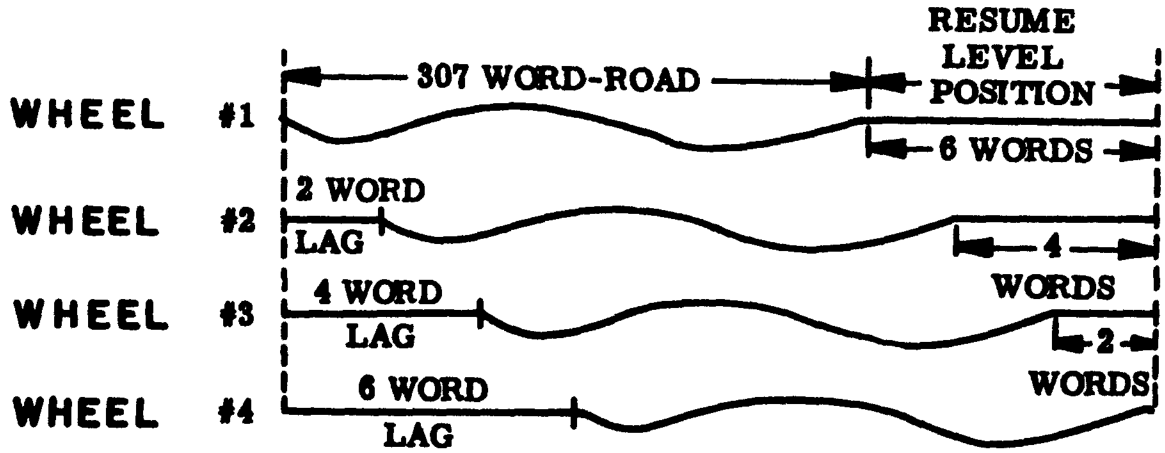


FIG. 3. ROAD PROFILE

The best procedure in this instance is to let one foot of road be represented by one computer word. However, if the spacing between wheels is uneven, a scheme utilizing several words to the linear foot would be required.

After the preliminary road function details have been accounted for, the actual generation of the road function can be undertaken. This naturally divides into the following steps:

1. Preparation of the data tape.

2. Placing road level data into computer memory.

3. Generation of the road function tape.

4. Transfer of the road function data to the digital-to-analog converter, etc.

Each computer "word" of information contains five channels, four of which are used for terrain simulation. Each of these channels may represent data. An algebraic representation of such a word is 1 aa bb cc dd 00, where each pair of letters represents one channel in the output of the Digital-Analog conversion system, while the number (1) in the sign position designates a particular group of D-A Converters, (Note that since the last channel is not used it is represented by 00, i.e. no information present). With proper scaling and programming, each channel can become a road-profile-wheel-terrain-function-generator (RPWTFG). Hence, there are four RPWTFG's per computer word.

The time between data increments on the computer is generated by using a time control subroutine which increases or decreases the time between "calling up" the data increments. The speed of the road function is determined from the recorder tracings as follows:

$$\text{mph} = \frac{\text{actual length of road (ft)}}{\text{length of converted road (mm)}} \times \text{paper speed} \left(\frac{\text{mm}}{\text{sec.}}\right) \times \frac{30 \text{ mph}}{44 \text{ ft/sec}}$$

By this procedure vehicle road speed is established. Maximum road speed is only limited by the computers ability to call up data. Utilization of a time delay subroutine within the computer facilitates decreasing the speed. Also, greater speed can be attained by shortening the road, i.e. picking up every second or every third road elevation. Oscillograph recordings, as generated by this system, are illustrated in Figure 4.

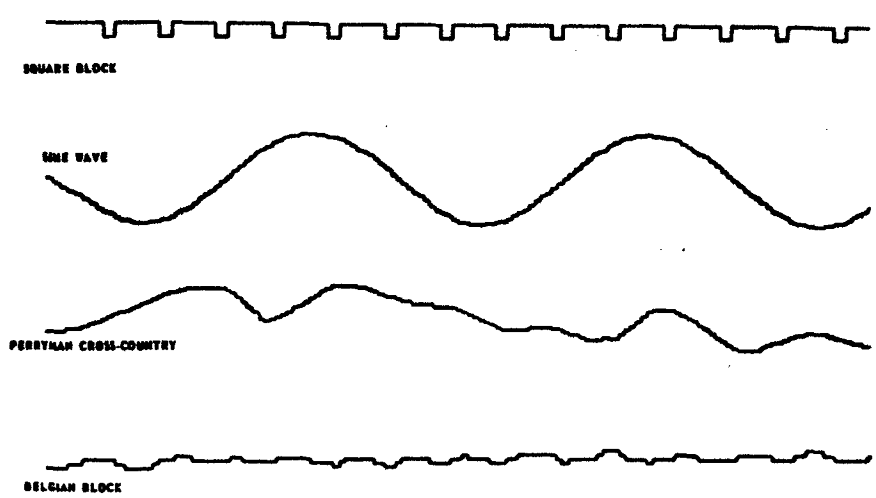


FIG. 4. ROAD PROFILE

A magnetic tape recorder and reproducer add convenience and efficiency to the system. By recording successive speeds on magnetic tape, the digital computer is used only once for a particular vehicle. In addition, velocity multiplication may be obtained by recording at one speed and reproducing at higher speeds.

Thus, any terrain that can be numerically described as increments of elevation with respect to horizontal distance, can be simulated with a digital computer for the analysis of vehicle behavior.

With the road prepared the simulation requires a model of the suspension system. For this purpose the Analog computer is best suited. The computer, as used, provides an accurate representation of the design. In a true sense the computer is an electronic model of the vehicle. The degree of realism achieved is naturally governed by the quantity of vehicle characteristics simulated.

As in any simulation, the system is first described by a mathematical model. The equations represent the dynamic system - the vehicle chassis, the suspension system and the road surface input.

Vehicular vibration components include the mass and inertia of the sprung components, the suspension springs, shock absorbers, road wheel masses, and the spring and damping characteristics of the wheel assembly.

The typical method of describing a vehicle to be simulated is shown in Figure 5 and Figure 6. From the diagrams, the equations of motion may be stated. These expressions are written as common linear differential equations with non-linear coefficients.

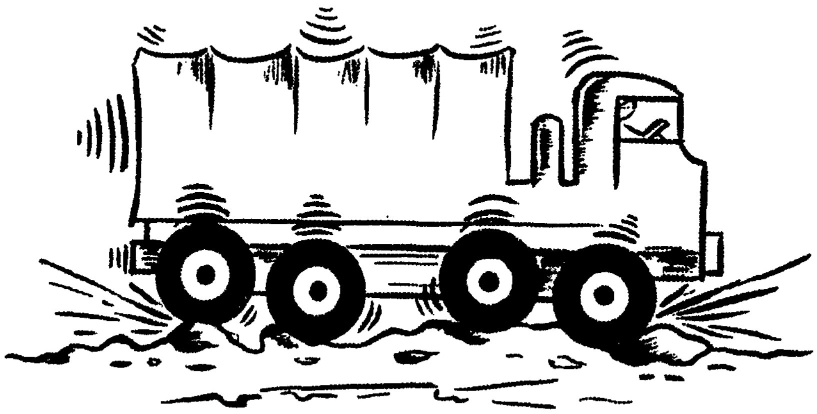


FIG. 5. VEHICLE CONFIGURATION

Non-linearities in the simulation exist normally due to non-linear spring characteristics, double acting shock absorbers, and the fact that wheels may leave the road surface.

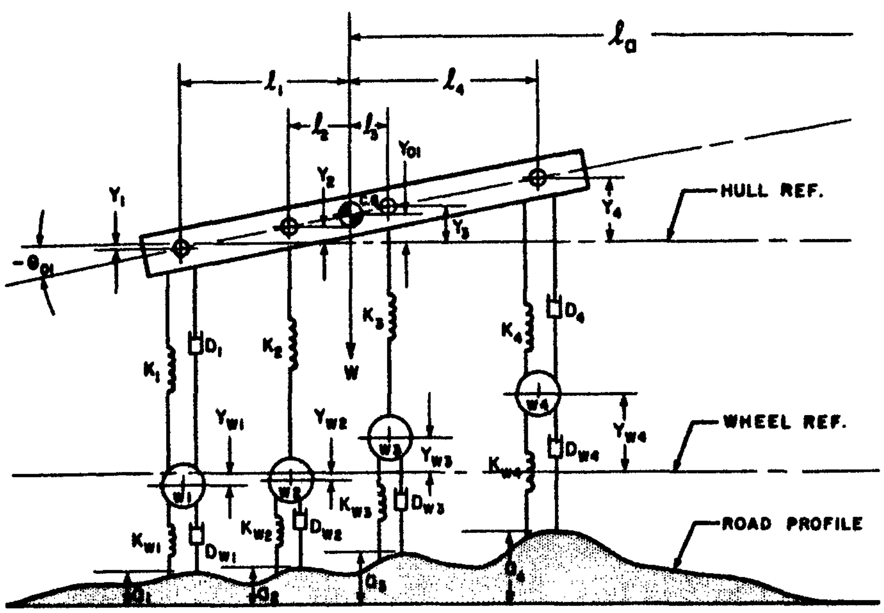


FIG. 6. VEHICLE SCHEMATIC

The equations result from linear and angular counterparts of Newton's second law of motion. The summation of the vertical forces on the chassis equals the mass of the chassis times its vertical acceleration; the summation of the torques about the center of gravity is equal to the polar moment of inertia times the angular acceleration of the hull. The forces and torques result from relative displacement and velocity of the springs and shock absorbers respectively. For example, the vertical force of the front wheel spring is equal to the spring constant (K_1) times the relative displacement between the wheel and the chassis just above the wheel. Similarly, the torque is a product of this force times the distance from the center of gravity. The shock absorber force is a product of the damping coefficient and the relative velocity between the wheel and the chassis above the wheel.

Chassis, pitch and bounce equations may be developed using these relationships. Separate differential equations are written to describe the motion of each wheel. Auxiliary equations are written to relate the pitch motion to the vertical motion so that the displacement and velocity of the chassis at each wheel station may be found.

Each wheel of the vehicle is considered a separate mass, spring, and damper system connected to the ground and to the chassis, the link to the chassis being the suspension spring and shock absorber. The force exerted on the wheel by the ground is equal to a product of the wheel rubber displacement and spring constant. This force may have only one sign since the ground cannot "pull" down on the wheel. The suspension spring force is also exerted on the wheel.

<u>Simulation Equations</u>:

<u>Chassis Vertical Motion</u>:

$$\ddot{Y}_o = \frac{\sum F_y}{M_o} \quad \text{(c.g. Bounce Acceleration)}$$

$$\ddot{Y}_o = -\frac{K_1}{M_o}(Y_1 - Y_{w1}) - \frac{K_2}{M_o}(Y_2 - Y_{w2}) - \frac{K_3}{M_o}(Y_3 - Y_{w3})$$

$$-\frac{K_4}{M_o}(Y_4 - Y_{w4}) - \frac{D_1}{M_o}(\dot{Y}_1 - \dot{Y}_{w1}) - \frac{D_4}{M_o}(\dot{Y}_4 - \dot{Y}_{w4}) + g$$

Chassis Pitch Motion:

$$\ddot{\theta} = \frac{\sum T}{J_O} \quad \text{(c.g. Angular Acceleration)}$$

$$\ddot{\theta} = -\frac{K_1 l_1}{J_O}(Y_1 - Y_{w1}) - \frac{K_2 l_2}{J_O}(Y_2 - Y_{w2})$$

$$+\frac{K_3 l_3}{J_O}(Y_3 - Y_{w3}) + \frac{K_4 l_4}{J_O}(Y_4 - Y_{w4})$$

$$-\frac{D_1 l_1}{J_O}(\dot{Y}_1 - \dot{Y}_{w1}) + \frac{D_4 l_4}{J_O}(\dot{Y}_4 - \dot{Y}_{w4})$$

Vertical Wheel Motion:

$$\ddot{Y}_w = \frac{\sum F_w}{M_w}$$

$$\ddot{Y}_{w1} = -\frac{K_{w1}}{M_{w1}}(Y_{w1} - a_1) - \frac{D_{w1}}{M_{w1}}(\dot{Y}_{w1} - \dot{a}_1) + \frac{K_1}{M_{w1}}(Y_1 - Y_{w1})$$

$$+\frac{D_1}{M_{w1}}(\dot{Y}_1 - \dot{Y}_{w1}) + g$$

$$\ddot{Y}_{w2} = -\frac{K_{w2}}{M_{w2}}(Y_{w2} - a_2) - \frac{D_{w2}}{M_{w2}}(\dot{Y}_{w2} - \dot{a}_2) + \frac{K_2}{M_{w2}}(Y_2 - Y_{w2}) + g$$

$$\ddot{Y}_{w3} = -\frac{K_{w3}}{M_{w3}}(Y_{w3} - a_3) - \frac{D_{w3}}{M_{w3}}(\dot{Y}_{w3} - \dot{a}_3) + \frac{K_3}{M_{w3}}(Y_3 - Y_{w3}) + g$$

$$\ddot{Y}_{w4} = -\frac{K_{w4}}{M_{w4}}(Y_{w4} - a_4) - \frac{D_{w4}}{M_{w4}}(\dot{Y}_{w4} - \dot{a}_4) + \frac{K_4}{M_{w4}}(Y_4 - Y_{w4})$$

$$+\frac{D_4}{M_{w4}}(\dot{Y}_4 - \dot{Y}_{w4}) + g$$

Auxiliary Chassis Equations:

$$Y_{1-4} = Y_o + \ell_{1-4}\ \mathrm{SIN}\ \theta \qquad \dot{Y}_{1-4} = \dot{Y}_o + \ell_{1-4}\ \mathrm{SIN}\ \theta$$

The non-linearities are best described in graphical form, as is shown in Figures 7 and 8.

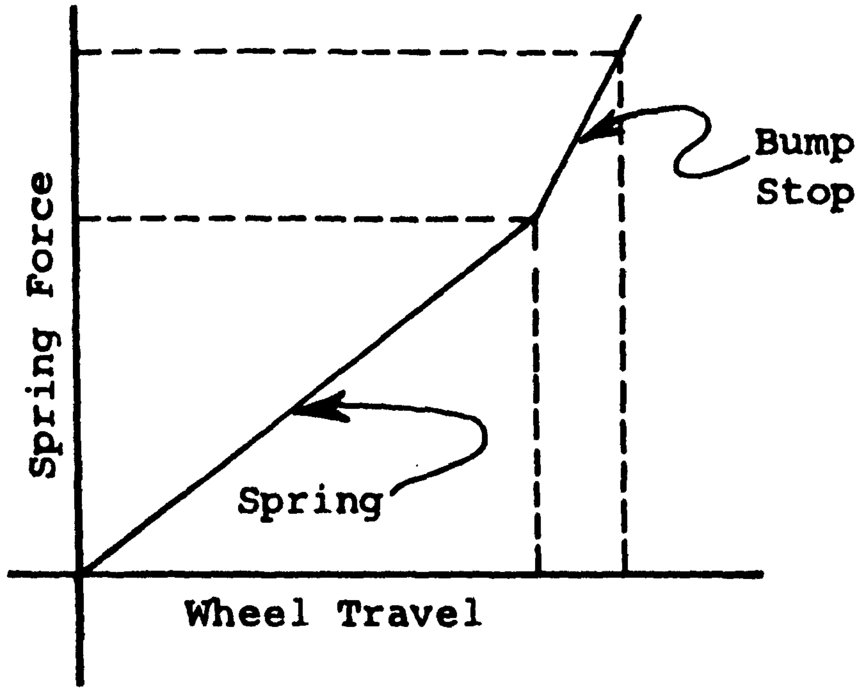


FIG. 7. SPRING LOAD VS WHEEL DEFLECTION

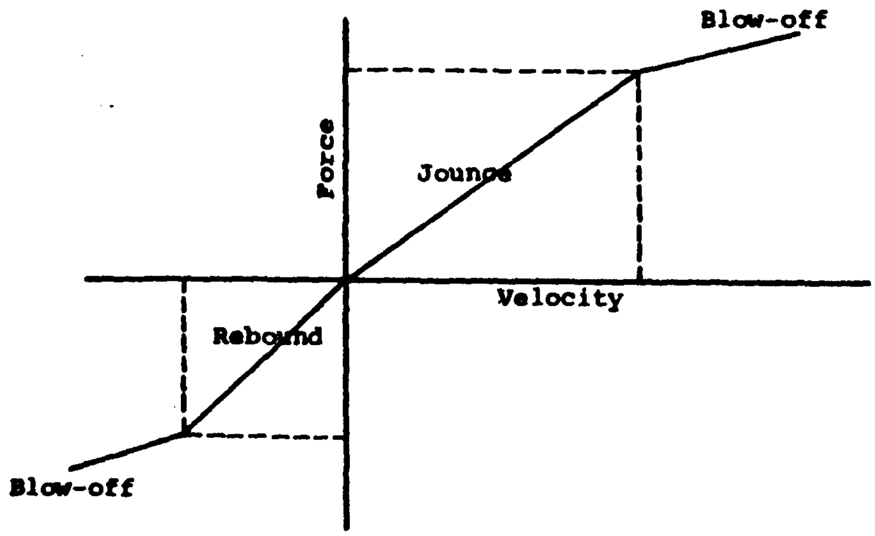


FIG. 8. SHOCK ABSORBER VS VELOCITY AT WHEEL

The non-linear suspension springing is composed of two linear segments, the one of lesser slope being the suspension spring, and the other the bump stop. The shock absorber non-linearity is shown in Fig. 8, which has four linear segments simulating different rates in compression and expansion with blow-off valves. The circuitry for creating the significant segments of a suspension simulation are shown in Figures 9 - 13. If a wheel leaves the ground, no spring force can exist between the ground and the wheel. To provide for this realistic action, a diode representing a unidirectional spring force is put in series with the wheel feedback loop, as is shown in the wheel circuit, Figure 11.

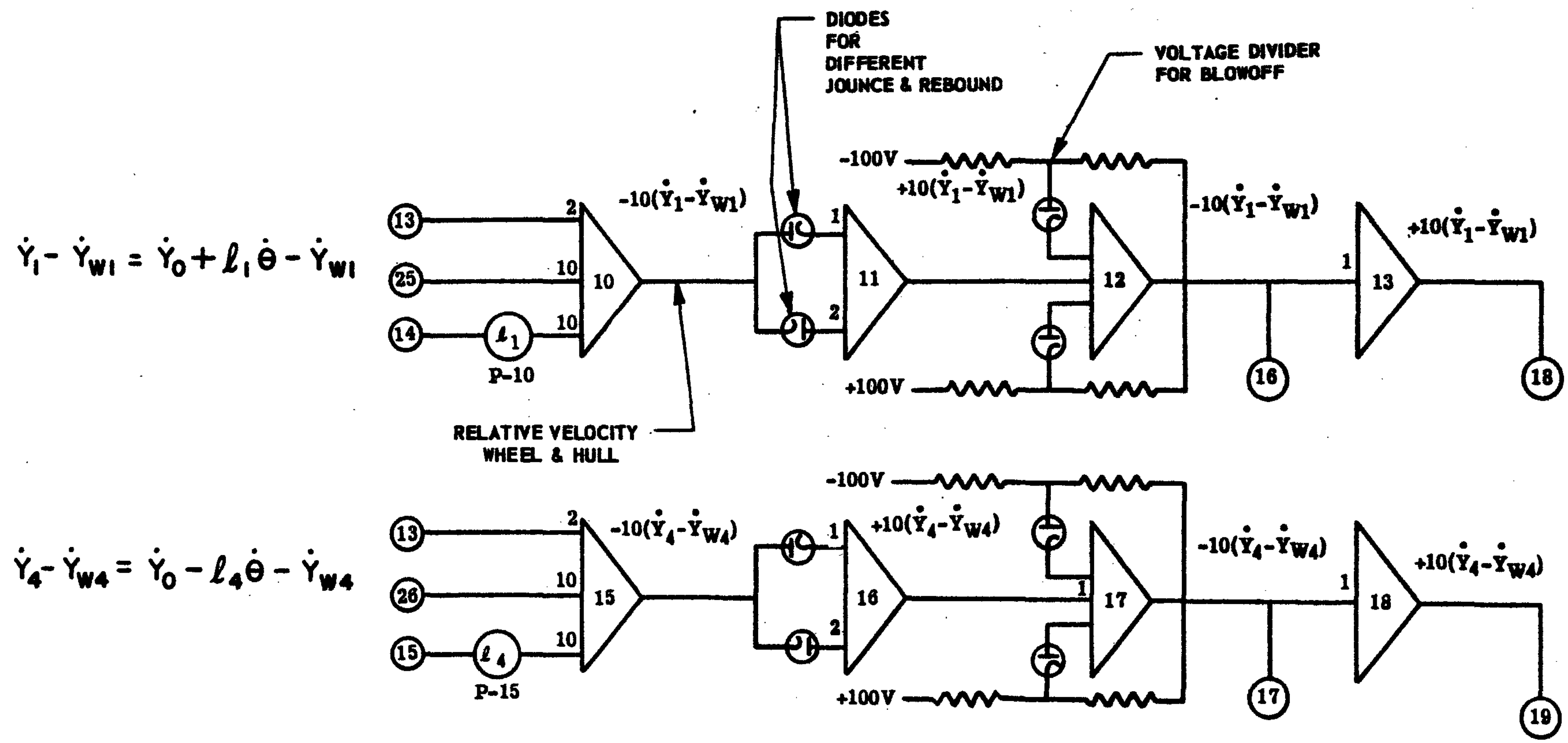


FIG. 9 SHOCK ABSORBER CIRCUITS

$$Y_1 - Y_{W1} = Y_0 + \ell_1\theta - Y_{W1}$$

$$Y_2 - Y_{W2} = Y_0 + \ell_2\theta - Y_{W2}$$

$$Y_3 - Y_{W3} = Y_0 - \ell_3\theta - Y_{W3}$$

$$Y_4 - Y_{W4} = Y_0 - \ell_4\theta - Y_{W4}$$

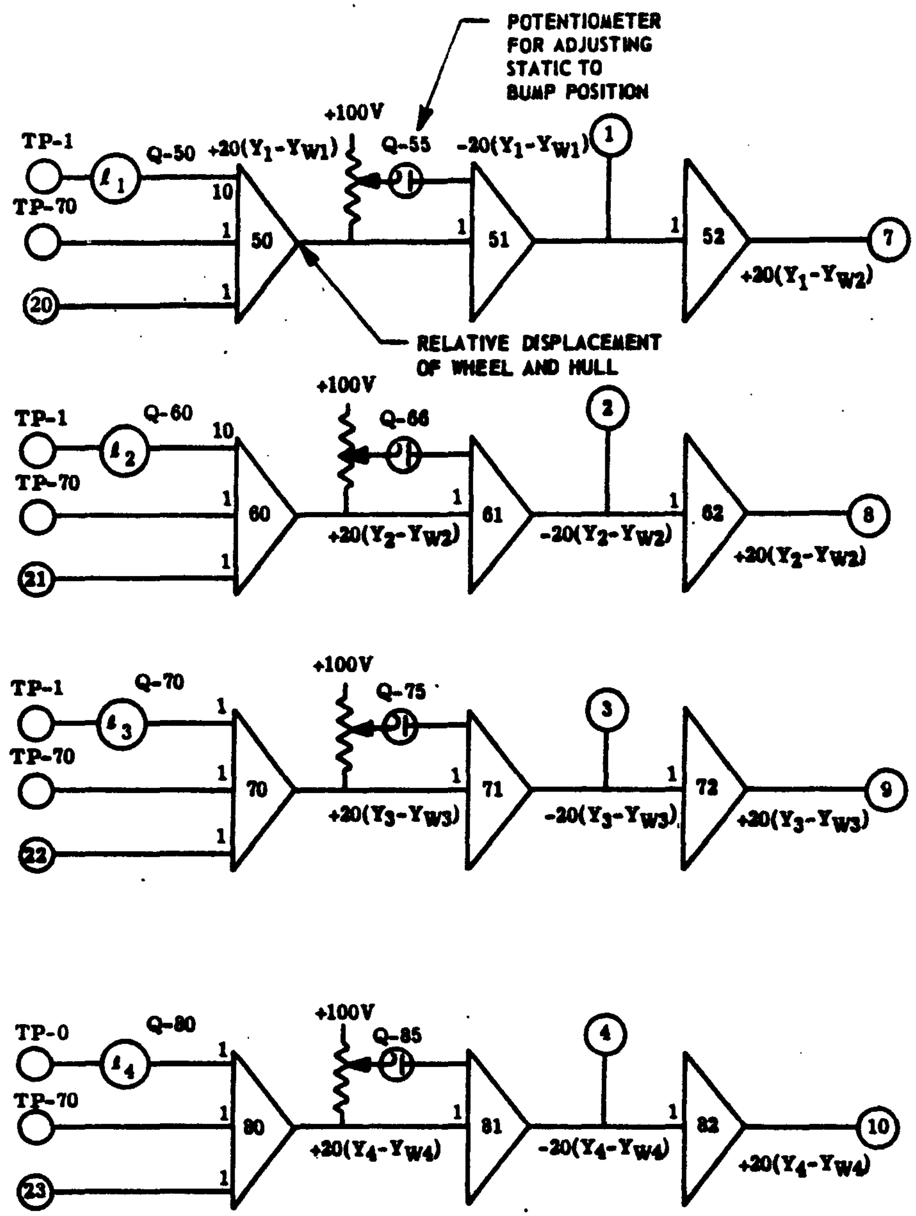


FIG. 10 SPRING CIRCUITS

$$\Sigma \frac{F_W}{M_W} = \ddot{Y}_W$$

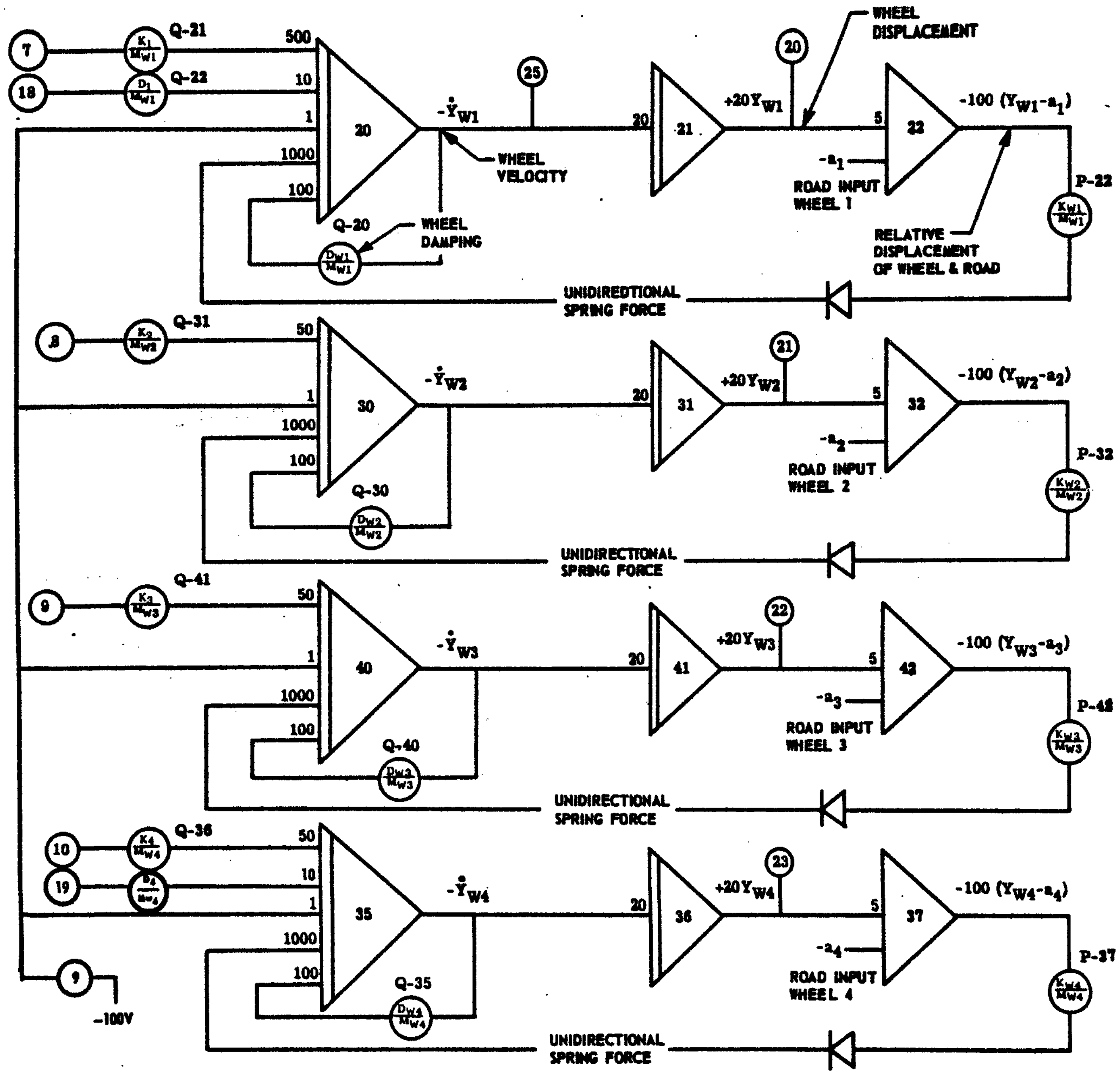


FIG. II WHEEL VELOCITY, AND DISPLACEMENT

$$\frac{\Sigma F_Y}{M_O} = \ddot{Y}_O$$

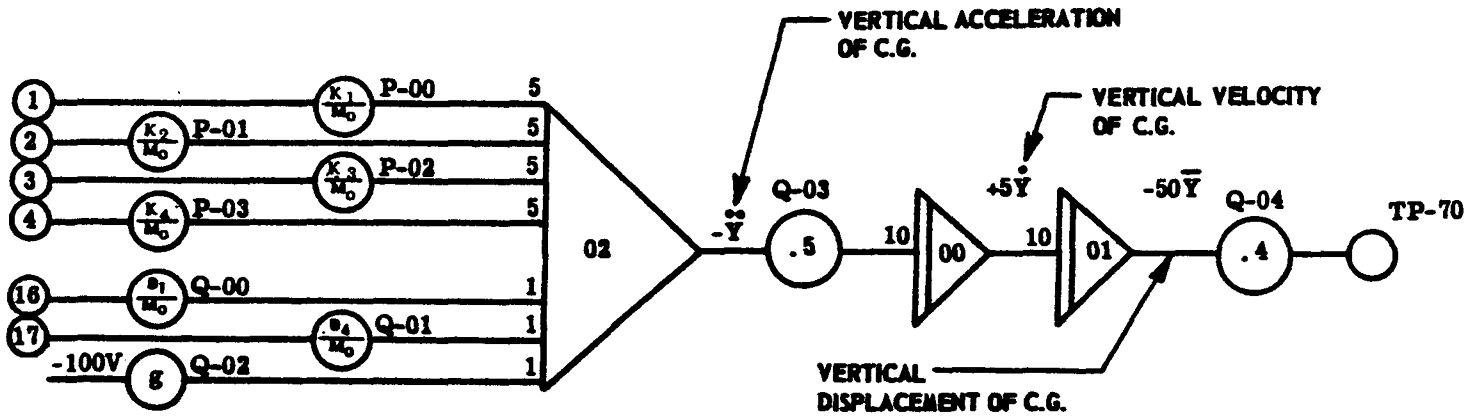


FIG. 12 C.G. VERTICAL ACCELERATION, VELOCITY, DISPLACEMENT

$$\frac{\Sigma T}{J_o} = \ddot{\theta}$$

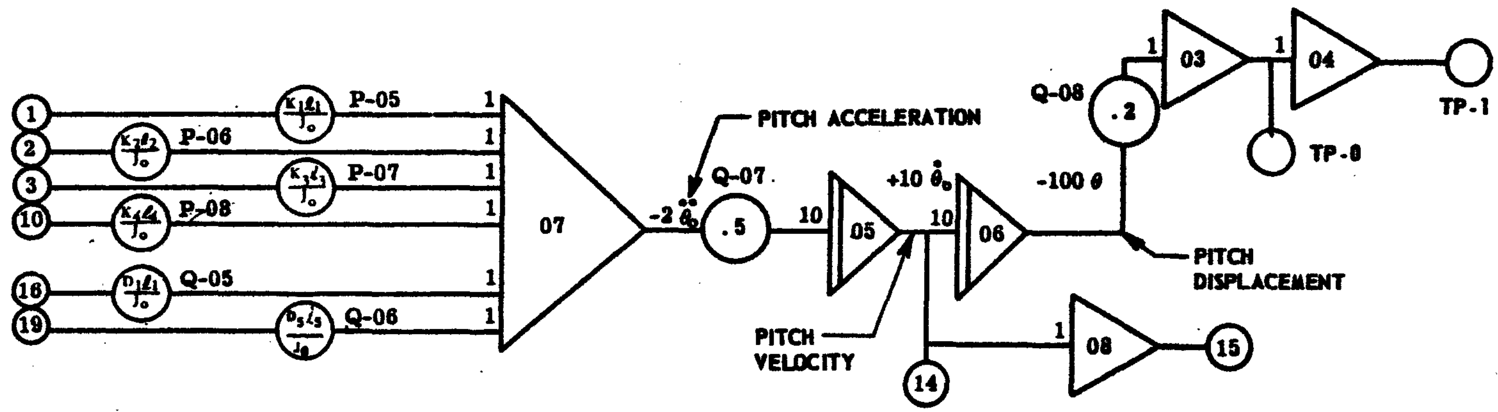
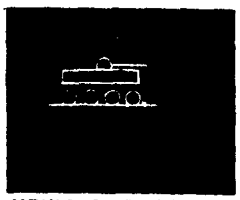
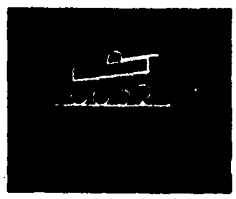


FIG. 13 C.G. PITCH ACCELERATION, VELOCITY, DISPLACEMENT

Simulation begins when the electronic version of a road and suspension system are brought together. Results are best analyzed using oscillographic or pen recorder output devices. Recorded paper tracings provide an excellent permanent record for lengthy detailed analysis. The oscillograph display system offers an opportunity to observe the simulation visually as an animated presentation. The dynamics of a complete vehicle or any component thereof may then be studied. This display system is used in conjunction with the analog computer. A cathode-ray-tube is used to convert the output voltages of the computer into a direct pictorial representation. Application of this system is shown in Figure 14. The series of photographs describe the motion of a tank that would be seen on the tube. The vehicle is shown negotiating at successive instances a 4" x 4" square obstacle.



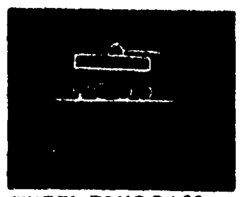
VEHICLE APPROACHING OBSTACLE



WHEEL ONE PASSING OVER OBSTACLE

WHEEL TWO PASSING OVER OBSTACLE

WHEEL THREE PASSING OVER OBSTACLE



WHEEL FOUR PASSING OVER OBSTACLE

FIG. 14. VISUAL DISPLAY SYSTEM

This visual display provides a quick and easy method of conducting a preliminary analysis of new suspensions. It is also a good means of debugging a new simulation setup.

Simulator:

Results of computer simulations may also be studied with the aid of a motion simulator. The value of the Simulator, Figure 15, lies in its ability to physically reproduce realistic "ride motion" that may be predicted by a computer simulation. Thus, by combining computer studies of new concepts with a simulator analysis, design merits may be judged in the laboratory by engineers, designers, and administrative people before a design is considered for fabrication. Each individual may ride a new suspension in the Simulator and personally evaluate his area of interest firsthand.

The Simulator described below is a four degree of freedom machine capable of providing bounce, pitch, roll and yaw motions.

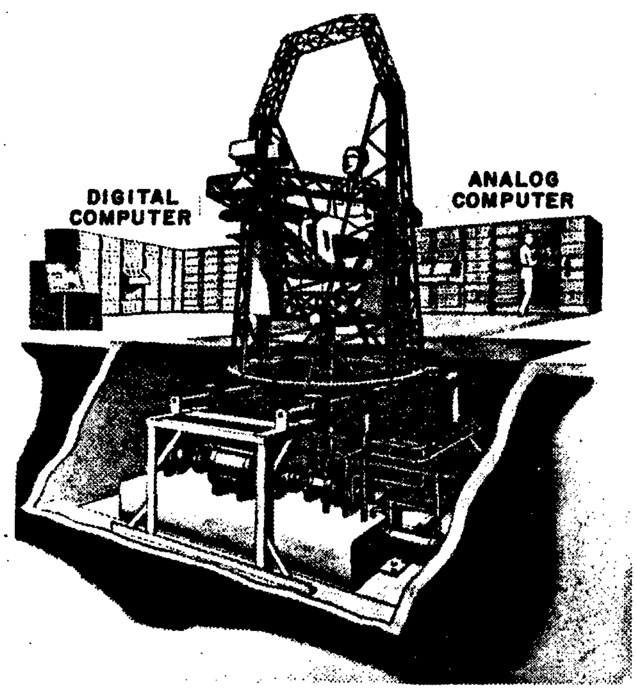


FIG. 15. SIMULATOR

The control of the machine is optional. The Simulator may be controlled from an instrument panel to produce either sine, square or triangular motions. Random motion inputs may be fed directly into the Simulator from an Analog computer simulation or by reproducing information previously recorded on magnetic tape.

This machine is hydraulically driven and electronically controlled. Each of the four motions may be used individually or simultaneously.

Motion	Max. Tot. Travel	Max. Frequency	Acceleration
Bounce	3 ft	10 cps	2 g's
Roll	40 deg	10 cps	30 radians/sec^2
Pitch	40 deg	10 cps	30 radians/sec^2
Yaw	20 deg	3 cps	15 radians/sec^2

Perhaps the most significant claim that can be broadcast for the Simulator, at this time, is that it will make possible performance trials of designs prior to building of a design. In some instances it is the only economical approach, considering time and cost, particularly, where a new design is being investigated using many alternatives.

The creation of this Simulator provides the Army Tank-Automotive Command with a design tool that has been sought for some time. The need for an instrument of this kind has been in continuous demand for military suspension studies and other shock and vibration programs.

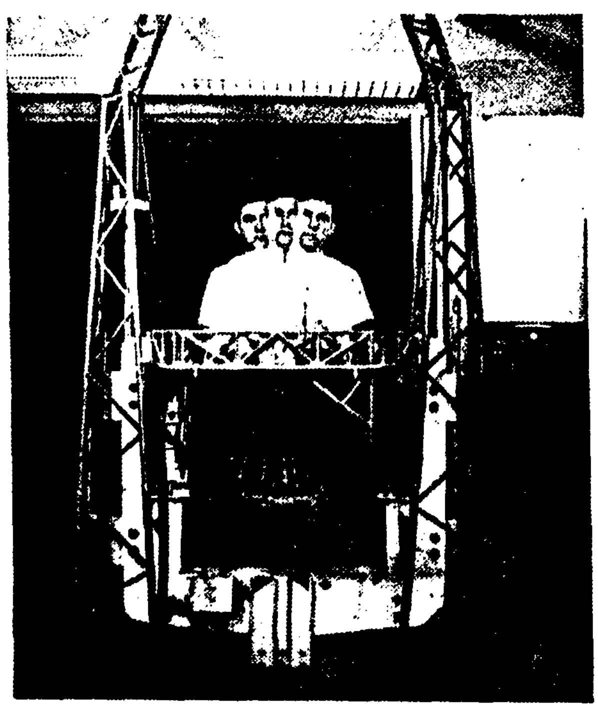


FIG. 16. DYNAMIC SIMULATION

The immediate response to the Simulator was generally favorable, but reserved. Comments usually indicated that the vibratory motions were good. However, it was repeatedly stated that the laboratory environment around the Simulator degraded the intended realism. The common complaint was that the "out of doors" atmosphere seemed to be missing.

To compensate for this a visual display was created providing a 180 degree field of view horizontally and 48 degrees in the vertical plane. A 35mm motion picture format was used to produce a "three screen" presentation. This method was selected, based upon successful tryouts of a unique projection system developed and tailored to the Simulator.

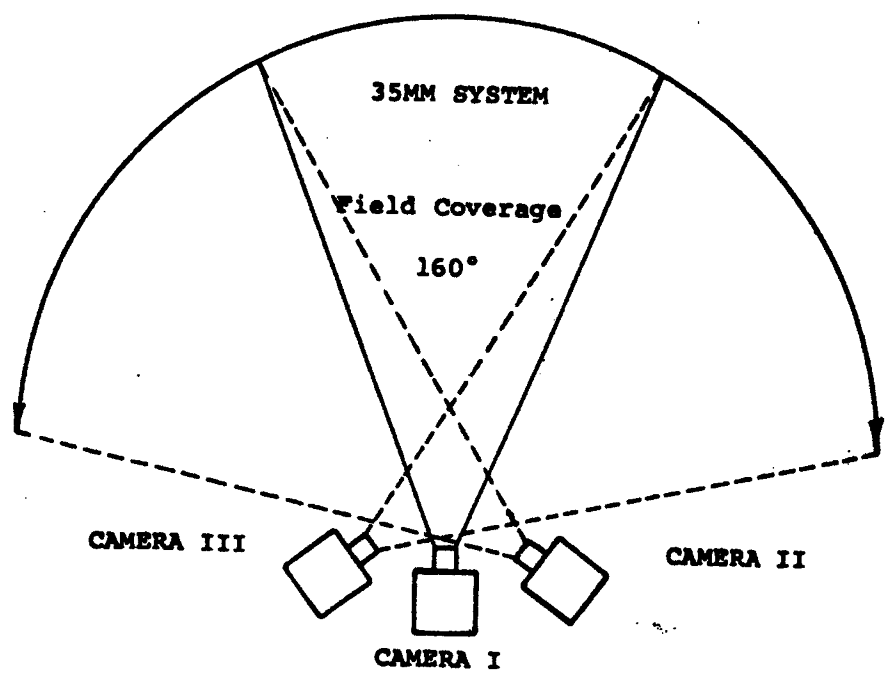


FIG. 17. CAMERA SYSTEM

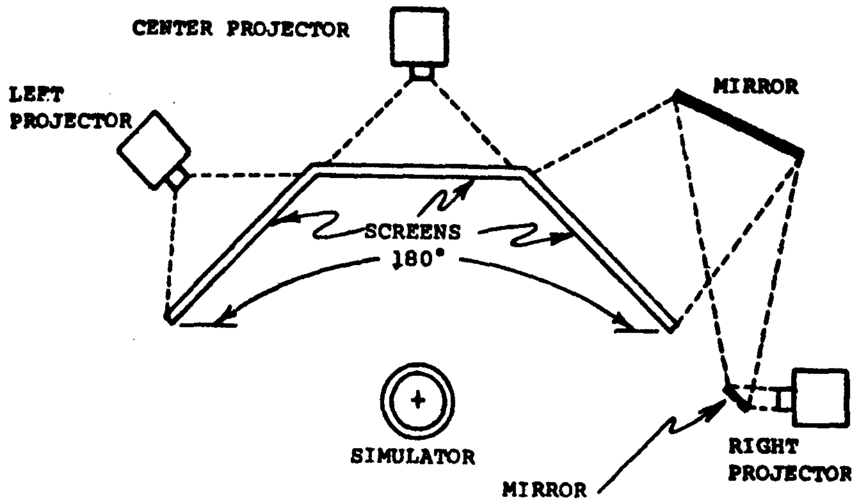


FIG. 18. PROJECTION SYSTEM

The activity scene is photographed by three cameras and backprojected to the subject in the Simulator by three synchronized-interlocked projectors. This system presents to the observer a scene that compares favorably to a view from within a moving vehicle.

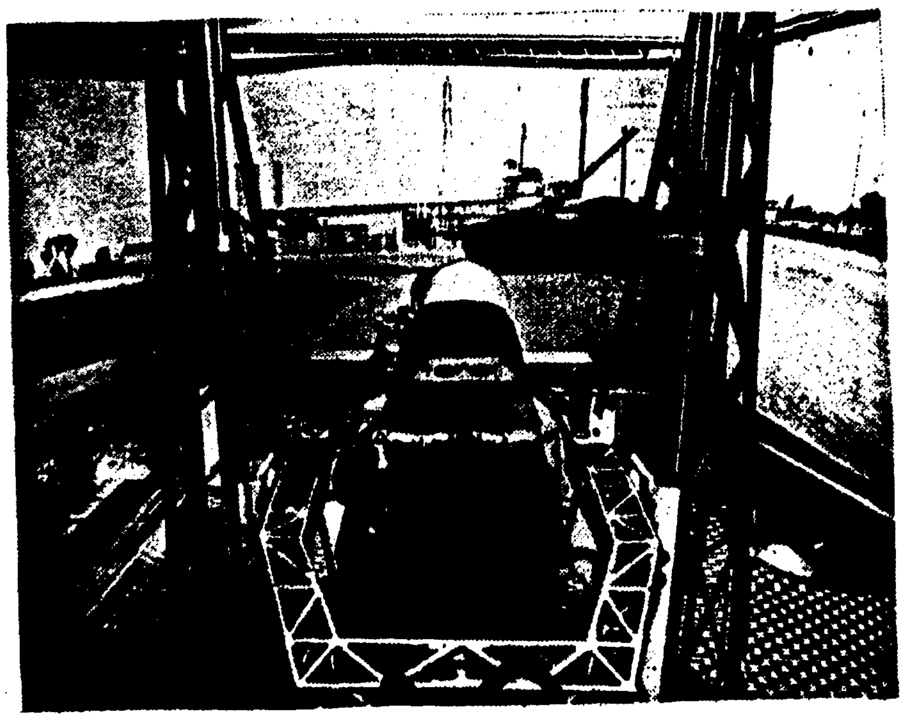


FIG. 19. DISPLAY SYSTEM

Vehicle Stability:

The Simulator was also used to simulate vehicle firing stability dynamics. The starting cue for this program was very forceably observed in vehicles like the Self-Propelled Artillery Weapon shown in Figure 20.

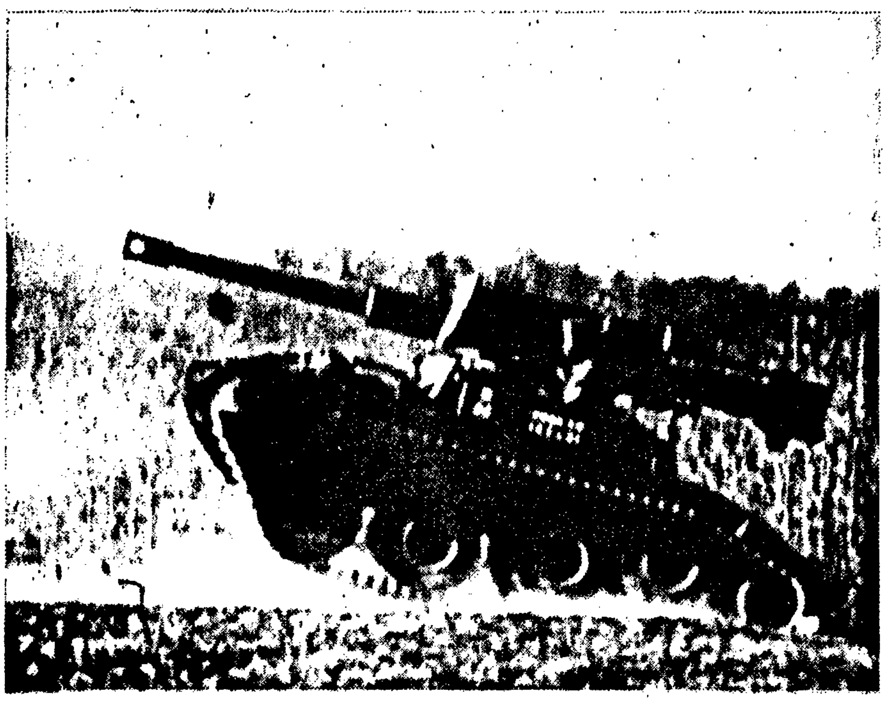


FIG. 20. SELF-PROPELLED ARTILLERY WEAPON

In keeping with this indicated trend of big guns on small chassis platforms it was necessary to establish with greater accuracy, the stability of contemplated designs.

The characteristic events describing fire stability were analyzed by charting the flow of events and establishing the equations of motion.

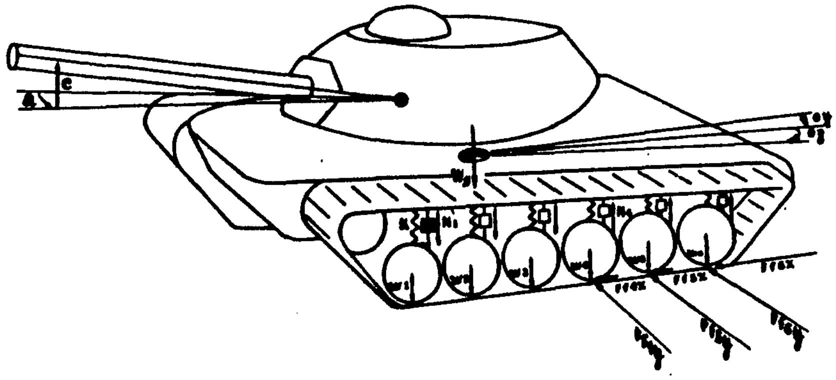


FIG. 21. VEHICLE SCHEMATIC

VEHICLE FIRING STABILITY FLOW DIAGRAM

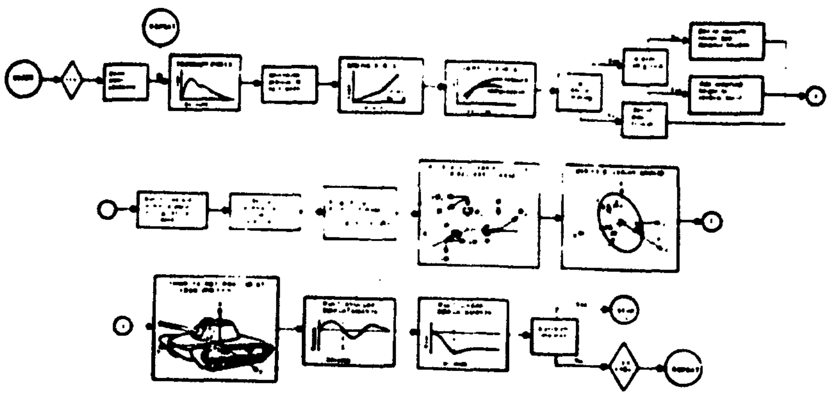


FIG. 22. FLOW DIAGRAM

Equations of Motion:

LONGITUDINAL TRANSLATION: GUN FORCE + GROUND FRICTIONAL FORCE = MASS X ACCELERATION $F_{gx} + F_{fx} = m\,(\ddot{x} - y\,\dot{\theta}_z + z\dot{\theta}_y)$

LATERAL TRANSLATION: GUN FORCE + GROUND FRICTIONAL FORCE = MASS X ACCELERATION $F_{gy} + F_{fy} = m\,(\ddot{y} - \dot{z}\dot{\theta}_x + \dot{x}\dot{\theta}_z)$

BOUNCE: GUN FORCE - SPRUNG WEIGHT + SUSPENSION FORCES = MASS X ACCELERATION $F_{gz} - W_s c_{zZ} + \sum_{i=1}^{n} N_i = m\,(\ddot{z} - \dot{x}\dot{\theta}_y + \dot{y}\dot{\theta}_x)$

ROLL: GUN MOMENT + GROUND FRICTIONAL MOMENT + SUSPENSIONAL MOMENT = ANGULAR ACCELERATION X MOMENT OF INERTIA $-\bar{z}F_{gy} + \bar{y}F_{gz} + (z + z_0)\, F_{fy}c_yY + \sum_{i=1}^{n} N_i Y_i = \ddot{\theta}_x I_x - \ddot{\theta}_z I_{xz} +$

$$(I_z - I_y)\, \theta_y\dot{\theta}_z - I_{xz}\dot{\theta}_x\dot{\theta}_y$$

PITCH: GUN MOMENT - GROUND FRICTIONAL MOMENT - SUSPENSIONAL MOMENT = ANGULAR ACCELERATION X MOMENT OF INERTIA $-\bar{x}F_{gz} + \bar{z}F_{gx} - (z + z_0)\, F_{fx}c_xX - \sum_{i=1}^{n} N_i x_i = \ddot{\theta}_y I_y + \dot{\theta}_x\dot{\theta}_x\,(I_x - I_z)$

$$+ (\dot{\theta}_x^2 - \dot{\theta}_z^2)\, I_{xz}$$

YAW: GUN MOMENT + GROUND FRICTIONAL MOMENTS = ANGULAR ACCELERATION X MOMENT OF INERTIA $-\bar{y}F_{gx} + \bar{x}F_{gy} + \sum_{i=1}^{n}$

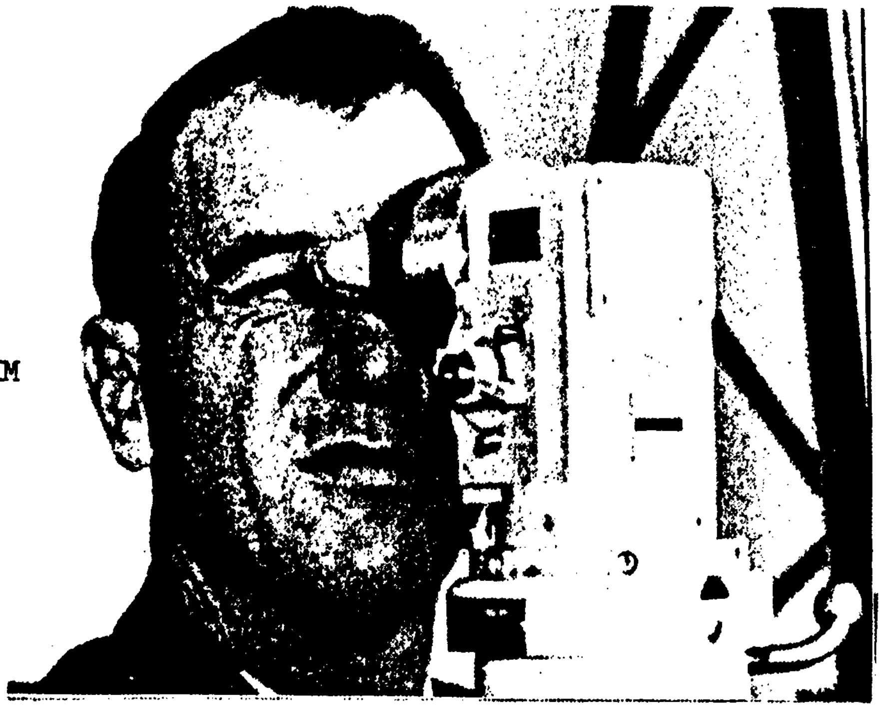
$x_i F_{fiy}\, c_yY - \sum_{i=1}^{n} y_i F_{fix} c_xX = \ddot{\theta}_z I_z - \ddot{\theta}_x I_{xz} +$

$(I_y - I_x)\;\; \dot{\theta}_x\dot{\theta}_y + I_{xz}\dot{\theta}_y\dot{\theta}_z$

The derived statements were for weapon systems free to move in three degrees of angular freedom - roll, pitch and yaw; and three degrees of translational freedom - fore and aft movement, bounce, and lateral slip. The equations define vehicle motion as effected by interrelated factors of gun firing force, gravity, terrain influence, and the resisting forces of the suspension.

The dynamics of firing stability are calculated on a digital computer. When this program is used in conjunction with the Simulator, the results are stored in computer memory. The physical arrangement of the Simulator permits the occupant to fire any weapon by merely pulling the usual trigger. The command to fire is completely controlled by the man in the seat.

AIM



FIRE

FIG. 23. FIRING SIMULATION

The inputs to this problem consist of various vehicle measurements, weights, moments of inertia, gun recoil force, type of soil, and type of suspension (active or locked-out). The output consists of detailed information in tabular or graph form showing angular and translational disturbances and their respective displacements, velocities, and accelerations with respect to time. This information describing gun firing force impact on the vehicle and resultant vibrations is available for the C.G. of the vehicle with reference to earth-fixed axes and for any other point on or within the vehicle, such as gun muzzle, engine mounts and crew stations with reference to the vehicle axes.

Summary:

The combination of computers and simulation techniques at the Army Tank-Automotive Command has provided an effective and versatile designer's tool. Informative preliminary studies have been conducted of new suspension systems and stability characteristics, without the use of hardware units of the design. Probes of unique approaches have quickly established design direction and payoff areas.

SUSPENSION NOMENCLATURE

$\ddot{Y}_O$ = Vertical acceleration of the center of gravity.

$\dot{Y}_O$ = Vertical velocity of C.G.

Y_O = Vertical displacement of C.G.

$\ddot{\theta}_O$ = Pitch acceleration about C.G.

$\dot{\theta}_O$ = Pitch velocity about C.G.

θ_O = Pitch displacement at C.G.

$(Y_1 - Y_{W1})$ = Relative displacement between hull and wheel at wheel 1.

$(\dot{Y}_1 - \dot{Y}_{W1})$ = Relative velocity of the hull and wheel at wheel 1.

$(Y_{W1} - a_1)$ = Relative displacement between wheel and input bump at wheel 1.

J_O = Pitch Moment of Inertia.

M_O = Sprung mass.

M_W = Wheel mass.

ℓ = Distance from wheel centerline to C.G.

K_{1-4} = Suspension spring constant.

D_{1-4} = Shock absorber damping constant.

K_W = Spring constant of road wheel rubber.

D_W = Damping constant of road wheel rubber.

a_{1-4} = Road inputs to wheel No. 1-4.

Y_{1-4} = Chassis displacement.

g = Acceleration of gravity.

VEHICLE STABILITY NOMENCLATURE

F_g = Gun force.

F_x = Frictional force.

W_s = Sprung weight.

M = Sprung mass.

$\bar{x}$, $\bar{y}$, $\bar{z}$ = Position of trunnion centerline.

z_o = Static height of C.G.

n = Number of wheels.

$\ddot{y}$, $\ddot{x}$, $\ddot{z}$ = Translational acceleration.

$\ddot{\theta}_x$ $\ddot{\theta}_y$ $\ddot{\theta}_z$ = Angular acceleration.

$\dot{y}$ $\dot{x}$ $\dot{z}$ = Translational velocity.

$\dot{\theta}_x$ $\dot{\theta}_y$ $\dot{\theta}_z$ = Angular velocity.

I = Moment of Inertia.

K = Suspension spring constant.

D = Shock absorber damping.

a = Gun azimuth.

e = Gun elevation.

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